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Modelling the Likelihood of Line-of-Sight for Air-to-Ground Radio Propagation in Urban Environments

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Abstract—The likelihood of line-of-sight (LoS) is an essential component in any radio channel model. It is particularly useful for radio network planning and urban coverage prediction. Empirical LoS models are hard to derive due to a strong dependency on local topology and the need for large measurement datasets. Since buildings are the major obstructions in a dense urban environment, we propose a new theoretical model to determine the LoS probability for air-to-ground channels based on local building geometry and knife-edge diffraction theory. The model takes into account key statistical parameters such as building height, building size, building coverage, street width and street angle distribution. The theoretical model is shown to agree well with ray tracing simulation results. The statistical parameters, such as mean building height, percentage of area covered by buildings (building coverage) and building density, can all be easily obtained for a specific location. We also derive equations for the likelihood of LoS for a direct slant path. These equations can be used in the analysis of air-to-ground channels.

Keywords—radio channel model; likelihood of line-of-sight (LoS); Fresnel zone; knife-edge diffraction; air-to-ground; urban.

I. INTRODUCTION

Many authors develop path loss models for line-of-sight (LoS) and non-line-of-sight (NLoS) radio channels; however they seldom consider the actual likelihood of achieving a LoS and NLoS connection. In theoretical studies, it is common for either a LoS channel, or a NLoS channel with log-Normal shadowing, to be assumed. The former assumption may be suitable for airborne radio links operating in open areas while the latter can be used for terrestrial peer-to-peer and microcellular radio channels. For air-to-ground (and ground-to-air) radio propagation in dense urban environments, there is a mix of LoS and NLoS conditions. Accurate channel models can be developed based on site-specific geometry (for example, ray tracing). The main disadvantage of this approach is the need for accurate building, foliage and terrain databases. Furthermore, obtaining results from geometric models can be very time-consuming and the results only apply to a site-specific region. To enable the use of simpler statistical channel models that address the air-to-ground link, in this paper we develop a general mathematical model for the likelihood of LoS.

Previous models based on measurements in European cities [1] [2] provided data on the likelihood of shadowing along typical streets at different elevation angles from satellites or helicopters. A theoretical physical model has also been

proposed by taking into consideration the distribution of building heights [3] [4], using canonical geometry similar to that used in this contribution. These papers focused on vehicles driving along the centre of a street, rather than randomly deployed terminals sited anywhere in the urban environment (such as next to a building wall). In [5], visibility in the form of theoretical optical LoS was investigated for a dense urban area.

The likelihood of LoS from a high mounted transceiver to randomly deployed terminals in a dense urban environment is essential for certain types of radio network planning and coverage analysis. Key examples include the development of emergency and disaster relief communication networks (where the use of terrestrial infrastructure may not be viable). Given that terminals can be located anywhere in the environment, the scenario becomes more complex than that of a vehicle moving along a street. We must consider a range of factors including street width, the amount of open area, and the street angle distributions. It is difficult to fit acceptable models for this scenario by measurements alone, since to create an accurate statistical model would require large amounts of data from similar environment types. Since buildings represent major scatters and commonly occlude the LoS component, the building height distribution has a strong effect on the radio propagation channel. Furthermore, it is necessary to consider building size, the percentage of area covered by buildings, the street width and the street angle. An air-to-ground channel model based on statistical geometry and radio propagation theory is therefore very useful to provide rapid and generic coverage information.

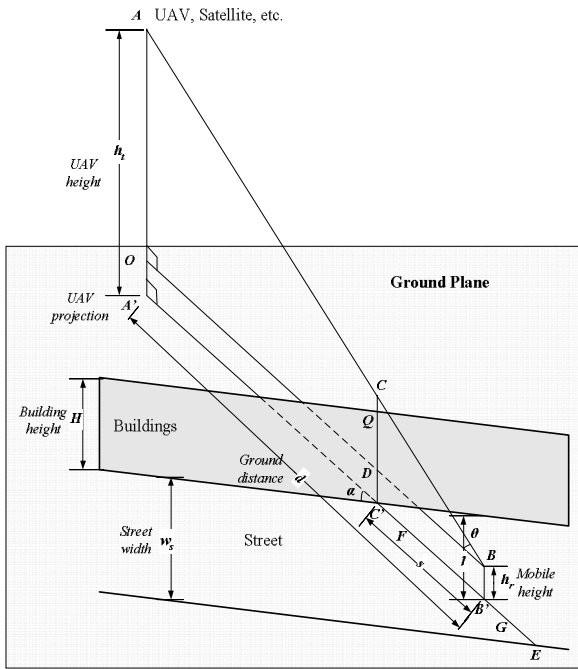
This paper first describes the canonical geometry used for air-to-ground channels. Next we obtain the condition for LoS determination for a slant direct path. The statistical model for LoS probability is then derived with particular attention given to the effective street width. Finally, the statistical model is verified via comparisons with a ray-tracing simulation for the centre of Bristol.

II. LOS DETERMINATION FOR AIR-TO-GROUND CHANNELS

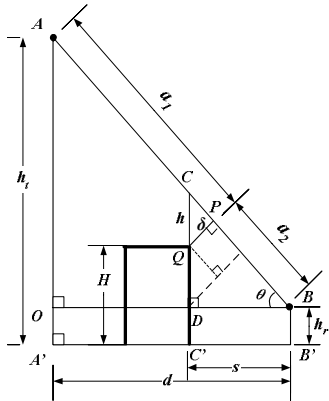
A radio channel is often classified as LoS or non-LoS dependent upon whether there exists a direct path between the transmitter and the receiver. In radio terms, LoS requires sufficient clearance of the first Fresnel zone. For air-to-ground channels, the building adjacent to the mobile in the direct path will be the dominant obstruction to radio propagation. Thus, a single knife-edge diffraction model can be used to determine the LoS condition.

Fig. 1 illustrates the canonical geometry for radio communications between a mobile (denoted as Rx) in the street and an airborne platform (denoted as Tx). This platform could be an aircraft, an unmanned air vehicle (UAV) or a satellite. The parameters in the geometry are as follows:

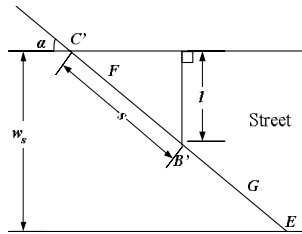
- 1) H - building height
- 2) w_s - street width
- 3) α - street angle (the angle of intersection between the street and the ground projections of the direct path)
- 4) s - distance from the mobile to its adjacent building along the direct path
- 5) l - perpendicular distance from the mobile to the street side
- 6) h_t - Tx height
- 7) h_r - Rx height
- 8) θ - elevation angle from Rx
- 9) d - Tx/Rx ground distance (distance between their projections on the ground)



(a) 3D overview



(b) Vertical plane



(c) Horizontal plane

Fig. 1. Geometry of LoS determination for a mobile in an urban street

Fig. 1(b) shows a building located between the Tx and Rx. According to knife-edge diffraction theory [6], the radius of the n^{th} Fresnel zone (r_n) and the Fresnel-Kirchhoff diffraction parameter (ν) are respectively:

$$r_n = \sqrt{\frac{n\lambda a_1 a_2}{a_1 + a_2}} \quad (1)$$

$$\nu = \delta \sqrt{\frac{2(a_1 + a_2)}{\lambda a_1 a_2}} = \frac{\delta \sqrt{2n}}{r_n} = \frac{\sqrt{2}\delta}{r_1} \quad (2)$$

where λ is the radio wavelength, δ is the distance from the direct path (which takes a negative value when the obstacle is below the direct path). The diffraction loss can be estimated from ν [6], and hence also from the ratio of δ to r_1 . When $\nu < -0.8$, the diffraction loss is approximately zero, and there is sufficient clearance of the first Fresnel zone. From (2), the LoS condition can also be represented as:

$$\delta < -0.56r_1. \quad (3)$$

δ can be obtained from Fig. 1(b) as:

$$\delta = \Delta H \cdot \cos \theta - s \cdot \sin \theta \quad (4)$$

where $\Delta H = H - h_r$ and r_1 can be obtained from (1). However, for air-to-ground channels, we can use a simplified representation which contains only the local geometry. When the airborne platform is much higher than the local buildings, the major on-roof diffraction arises from the adjacent building along the direct path. Thus, $a_1 \gg a_2$, i.e. $a_1 + a_2 \approx a_1$. Hence

$$r_n \approx \sqrt{n\lambda a_2} \quad (5)$$

where a_2 can be obtained from

$$a_2 = \Delta H \cdot \sin \theta + s \cdot \cos \theta \quad (6)$$

Then, the LoS condition is determined from (3), (4), (5) and (6) by the radio wavelength λ , the elevation angle θ and the local variables ΔH and s .

Transforming (3) into its quadratic form we get:

$$\sin^2 \theta \cdot s^2 + \cos^2 \theta \cdot \Delta H^2 - 2 \sin \theta \cos \theta \cdot s \Delta H - 0.32\lambda \cos \theta \cdot s - 0.32\lambda \sin \theta \cdot \Delta H > 0, \quad (7)$$

Then, the conditions of ΔH and s for LoS clearance can be obtained as:

$$\Delta H < s \tan \theta + \frac{0.16\lambda \sin \theta - \sqrt{0.16^2 \lambda^2 \sin^2 \theta + 0.32\lambda s \cos \theta}}{\cos^2 \theta} \quad (8)$$

$$s > \Delta H \cot \theta + \frac{0.16\lambda \cos \theta + \sqrt{0.16^2 \lambda^2 \cos^2 \theta + 0.32\lambda \Delta H \sin \theta}}{\sin^2 \theta} \quad (9)$$

From Fig. 1, $s = l / \sin \alpha$, thus the conditions for LoS with respect to l and α can be represented by (9). We denote the critical values for H , s , l and α as H_c , s_c , l_c and α_c respectively.

Equations (8) and (9) consist of two parts: the first part is the basic allowance incurred by the optical LoS; the second part is the extra allowance incurred by the thickened ray due to the first Fresnel zone. When the operating frequency is very high, the additional Fresnel zone component is very small and the optical component is sufficient. Particularly for optical LoS, (8) and (9) demonstrate linear relationships; thus, provided that the probability function of l (or H) is approximately symmetric, the variation of l (or H) does not significantly affect the statistical prediction of the LoS probability.

We can estimate LoS probability for two basic scenarios:

(1) *for a vehicle moving along the street*: Dependent on the building height cumulative distribution function (CDF) $D_H(H)$, the LoS probability in terms of s can be estimated using (8):

$$P_{LoS} = P(H < H_c) = D_H(H_c). \quad (10)$$

This is the scenario reported in [1] [2] and [4], which uses the term ‘time share of the shadowing’ instead of the LoS probability. The time share of the shadowing A is determined by the complementary of the building height CDF, i.e. $A = 1 - D_H(H_c)$.

(2) *for randomly deployed mobiles in the street or a city centre area*: Given the distribution function of the perpendicular distance to the street side l (or/and that of the street angle α), the LoS probability as a function of the building height H can be estimated using (9). This second case is developed in this paper.

III. LOS PROBABILITY MODELS FOR RANDOMLY DEPLOYED MOBILES

When the mobiles are randomly deployed in a street or an urban area, l becomes a random variable. The first (major) part of the right hand side of (9) i.e. $(H - h_r) \cot \theta$, is linearly related to the building height, for a given mobile height and elevation angle. Thus, provided that the PDF of the building height is approximately symmetrical about the mean, and l (and thus s) is uniformly distributed, a uniform building height is sufficiently accurate to statistically model the LoS probability, since the lower heights are cancelled by the higher heights due to the linear relationship between l_c and H for a short wavelength.

A. LoS probability in a street

As shown in Fig. 1, if the mobiles are uniformly randomly deployed in the street, then the distance to the street side is a uniformly distributed random variable in the range $[0, w_s]$. Thus its PDF and CDF are respectively [7]:

$$p_l(l) = \begin{cases} 1/w_s, & 0 < l < w_s \\ 0, & \text{otherwise} \end{cases} \quad (11)$$

$$D_l(l) = \begin{cases} l/w_s & 0 < l < w_s \\ 1 & l > w_s \end{cases} \quad (12)$$

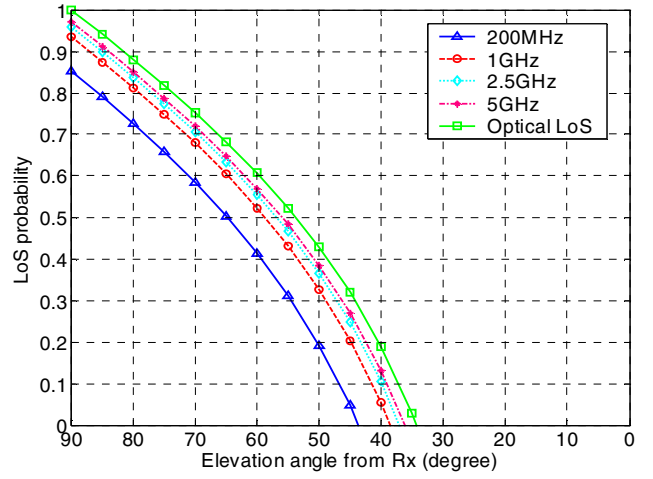


Fig. 2. LoS probability in street level (street angle 90°)

Since a LoS path exists only if the separation from the building is larger than l_c , the LoS probability is given by:

$$P_{LoS} = P(l > l_c) = \int_{l_c}^{w_s} p_l(l) dl = 1 - D_l(l_c) = \begin{cases} 1 - \frac{s_c \sin \alpha}{w_s}, & 0 < s_c < w_s / \sin \alpha \\ 0, & s_c > w_s / \sin \alpha \end{cases} \quad (13)$$

When only the optical LoS is considered, equation (13) becomes, in terms of the elevation angle

$$P_{LoS}(\theta) = \begin{cases} 1 - \frac{H - h_r}{w_s} \sin \alpha \cot \theta, & \tan \theta \geq \frac{H - h_r}{w_s} \sin \alpha \\ 0, & \text{otherwise} \end{cases} \quad (14)$$

and in terms of the ground distance and the Tx height

$$P_{LoS}(d) = \begin{cases} 1 - \frac{H - h_r}{w_s} \frac{\sin \alpha}{h_t - h_r} d, & d \leq \frac{w_s}{H - h_r} \frac{h_t - h_r}{\sin \alpha} \\ 0, & \text{otherwise} \end{cases} \quad (15)$$

In the centre of Bristol the average height of a building H is equal to 11.71m. For a street of width w_s of 15m, an angle α of 90°, and a mobile height h_r of 1.5m, the LoS probability as a function of elevation angle from the mobile at a series of frequencies (together with the optical LoS) are shown in Fig. 2.

B. LoS probability in an area

The LoS probability in an area can be estimated by the statistical average of the LoS probabilities in all the streets; thus, we take all the variations in street width and street angle into account. We assume an effective uniform street width w_e , which is discussed in more detail later. For a typical European city, the street is dense, and irregular in size and orientation. We divide a *bendy* street into a series of straight lines (mini-streets). The mini-street angle may be modelled as a uniform distribution between $[0, \pi/2]$; thus its PDF can be represented over $[0, \pi/2]$ as:

$$p_\alpha(\alpha) = \frac{1}{\pi/2} = \frac{2}{\pi}. \quad (16)$$

Then, the mean LoS probability in the operating area is given by

$$\overline{P_{LoS}} = E(P_{LoS}(\alpha)) = \int_0^{\frac{\pi}{2}} P_{LoS}(\alpha) p_{\alpha}(\alpha) d\alpha. \quad (17)$$

From (13), $P_{LoS} \neq 0$ only if $\sin \alpha \leq w_e / s_c$. We define α_c as the critical (maximum) angle

$$\sin \alpha_c = \begin{cases} w_e / s_c, & w_e \leq s_c \\ 1, & \text{otherwise} \end{cases},$$

then

$$\begin{aligned} \overline{P_{LoS}} &= \int_0^{\alpha_c} (1 - \frac{s_c}{w_e} \sin \alpha) \frac{2}{\pi} d\alpha + \int_{\alpha_c}^{\frac{\pi}{2}} 0 \cdot \frac{2}{\pi} d\alpha \\ &= \frac{2}{\pi} \alpha_c - \frac{2}{\pi} \frac{s_c}{w_e} (1 - \cos \alpha_c) \end{aligned} \quad (18)$$

When only the optical LoS is considered, the equations become:

$$\overline{P_{LoS}(\theta)} = \frac{2}{\pi} \alpha_c - \frac{2}{\pi} \frac{H - h_r}{w_e} \cot \theta (1 - \cos \alpha_c) \quad (19)$$

$$\overline{P_{LoS}(d)} = \frac{2}{\pi} \alpha_c - \frac{2}{\pi} \frac{H - h_r}{w_e} \frac{d}{h_t - h_r} (1 - \cos \alpha_c) \quad (20)$$

C. Estimation of street width w_e

Initially, w_s is defined as the street width, which is around 10-20 meters for the central area of Bristol. This value can be used for LoS probability at the street-level. However, the street width is not uniform, and moreover, there are usually open areas as well as street canyons in an urban environment. Thus, to estimate the statistical LoS probability in an urban environment, an average effective street width w_e is introduced.

Streets are formed by the separations between adjacent buildings. If we treat a cluster of concatenated buildings (e.g. a terraced set of houses) as a building, then for an area with a high building concentration, the number of buildings in the area is approximately equal to the number of streets. We define the number of buildings (or streets) per unit area as the building (street) density q . We also define the percentage of area covered by buildings as the building coverage ratio p . The street coverage ratio is $1 - p$. The average area covered by a street is $S_{St} = (1 - p) / q$. Assuming that the streets lie in a rectangular shape, and the relationship between the average length L and the effective width is $L = \gamma_0 w_e$, then $S_{St} = L w_e = \gamma_0 w_e^2$, where γ_0 is a constant. Hence,

$$w_e = \sqrt{\frac{1 - p}{\gamma_0 q}} = \gamma_1 \sqrt{\frac{1 - p}{q}} \quad (21)$$

where $\gamma_1 = 1 / \sqrt{\gamma_0} = \sqrt{w_e / L}$. Taking into account open areas, w_e can often be fairly large and hence the factor γ_1 is not often small. We will show later that for the centre of Bristol $\gamma_1 = 1$ gives a good approximation.

Given a digital map, the total area S , the building coverage area S_b , and the number of buildings N are easy to derive.

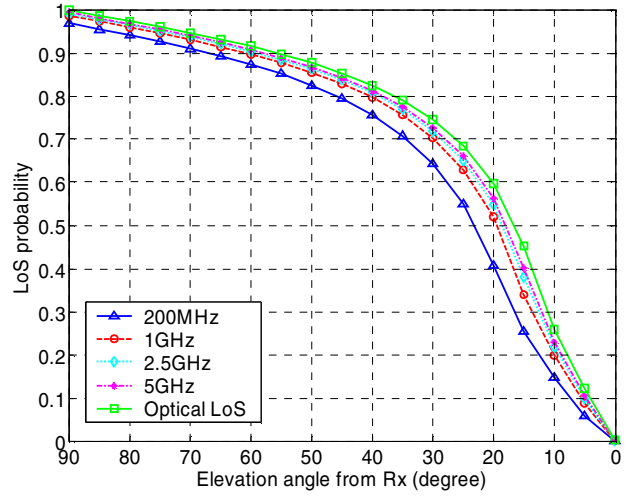


Fig. 3. Mean LoS probability in Bristol city centre

Using these values, the parameters in (21) can be obtained: $p = S_b / S$, $q = N / S$. Thus, (21) can also be represented as:

$$w_e = \gamma_1 \sqrt{\frac{1 - S_b / S}{N / S}} = \gamma_1 \sqrt{\frac{S - S_b}{N}} \quad (22)$$

For a $1.4\text{km} \times 1.4\text{km}$ area of central Bristol, the number of buildings $N = 717$, and the building coverage area $S_b = 0.552\text{km}^2$. Then, $p = 28.15\%$, $q = 365.82$ buildings / km^2 . Assuming $\gamma_1 = 1$, then $w_e = 44.2\text{m}$. The mean LoS probability as a function of elevation angle for a series of frequencies (together with the optical LoS) are shown in Fig. 3.

The required statistical parameters for our model, i.e. the mean building height H , the building coverage p and the building density q , are very easy to extract from the geographic database.

IV. VERIFICATION BY SIMULATION

The model is now verified using ray tracing computer simulations for different building and terrain profiles. The operating environment is a $1400\text{m} \times 1400\text{m}$ area of central Bristol. We place mobile nodes at more than 350,000 locations with a grid spacing of 2m and a terminal height of 1.5m above ground level (AGL). Nine airborne nodes are deployed at heights of 100m, 200m, 500m, 1000m and 2000m respectively. LoS status is determined by checking the obstacles between the Tx and Rx using geometrical methods and diffraction theory. The mean LoS probabilities are obtained as a function of elevation angle and Tx/Rx ground distance.

Fig. 4 shows plots of the mathematical model (unmarked solid curves) versus simulation results obtained using the actual geographic data for the central Bristol area. There is seen to be very good agreement between the derived LoS probabilities and the optical LoS probabilities extracted from the geographic data.

By doubling the heights of the buildings, we increase both the mean height and the standard deviation. As shown in Fig. 5, it can be seen that the model still performs well for such a high building height variation.

The area of central Bristol is hilly. Halving the terrain irregularity, we find that the LoS probability does not change significantly, as shown in Fig. 6. Terrain irregularity can have a significant impact on terrestrial mobile communications, particularly peer-to-peer mobile radio channels. However, for air-to-ground channels, where the height of the airborne platform is much larger than the terrain irregularity (which is usually the case for cities) LoS status is mainly determined by

the building height relative to the local terrain height. Thus, terrain irregularity has only a small impact on LoS probability for air-to-ground channels.

Altogether, simulation results indicate that the terrain irregularity and the building height variance have little influence on the mean LoS probability, and thus a uniform building height can be used for predictions. The results also justify the use of other assumptions, such as a uniform street angle and the use of an effective street width w_e .

V. CONCLUSIONS

This paper provides a prediction model for the likelihood of LoS for air-to-ground communications in dense urban environments. The model provides an essential supplement to existing path loss models for LoS/NLoS channels. Since we assume uniform street angles, the model is most suited to typical European cities with dense and irregular streets in direction, length and width. Further work is required to determine if the model is suited to other city types. The uniform distribution of street angles also implies that multiple airborne platforms deployed above an area in a circular disc shape may provide the highest likelihood of LoS.

Typical applications of this work include coverage prediction for emergency and disaster relief networks. When airborne nodes are deployed as relays, the range of peer-to-peer mobile networks can be significantly improved.

REFERENCES

- [1] E. Lutz, D. Cygan, M. Dippold, F. Dolainsky, and W. Papke, "The land mobile satellite communication channel - recording, statistics, and channel model," *IEEE Trans. Veh. Technol.*, vol. 40, no. 2, pp. 375–386, May 1991.
- [2] A. Kanatas and P. Constantinou, "City center high-elevation angle propagation measurements at L band for land mobile satellite systems," *IEEE Trans. Veh. Technol.*, vol. 47, no. 3, pp. 1002–1011, Aug. 1998.
- [3] S. Saunders and B. Evans, "Physical model of shadowing probability for land mobile satellite propagation," *Electronics Letters*, vol. 32, no. 17, pp. 1548–1549, Aug. 1996.
- [4] S. Saunders, C. Tzaras, and B. Evans, "Physical-statistical methods for determining state transition probabilities in mobile-satellite channel models," *International Journal of Satellite Communications*, vol. 19, no. 3, pp. 207–222, May 2001.
- [5] E. Ogawa and A. Satoh, "Propagation Path Visibility Estimation for Radio Local Distribution Systems in Built-Up Areas," *IEEE Trans. Commun.*, vol. COM-34, no. 7, pp. 721–724, July 1986.
- [6] J. Parsons, *The Mobile Radio Propagation Channel*, 2nd ed. West Sussex, England: Wiley, 2001.
- [7] R. Walpole, R. Myers, S. Myers, and K. Ye, *Probability & Statistics for Engineers & Scientists*, 7th ed. Upper Saddle River, NJ: Prentice Hall, 2002.

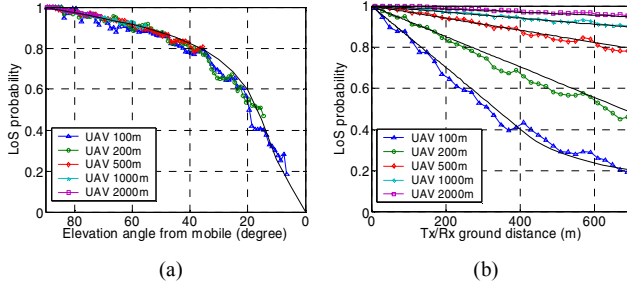


Fig. 4. Optical LoS probability in central Bristol area

(Unmarked solid black lines are results from the mathematical model)
(building height mean 11.71m, std. 5.51m; terrain std. 17.47m)

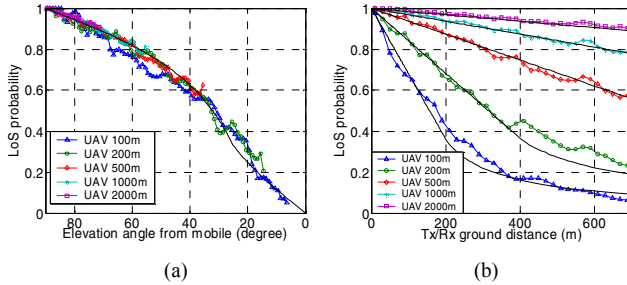


Fig. 5. Optical LoS probability for a modified database of central Bristol

(Unmarked solid black lines are results from the mathematical model)
(building height mean 23.42m, std. 11.02m; terrain std. 17.47m)

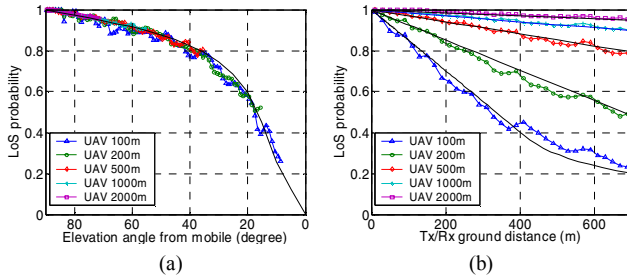


Fig. 6. Optical LoS probability for a modified database of central Bristol

(Unmarked solid black lines are results from the mathematical model)
(building height mean 11.71m, std. 5.51m; terrain std. 8.73m)